LITANI RIVER BASIN MANAGEMENT SUPPORT PROGRAM

QARAOUN RESERVOIR BATHYMETRIC SURVEY

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Contract No.: EPP-I-00-04-00024-00 order no 7.

AUGUST 2013

DISCLAIMER

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ACRONYMS

ASL	Above Sea Level (altitude)
GIS	Geographic Information System
GPS	Global Positioning System
LRA	Litani River Authority
LRBMS	Litani River Basin Management Support Program
RS	RiverSurveyor®
RSL	River Surveyor Live Software
HDOP	Horizontal Dilution of Precision

EXECUTIVE SUMMARY

PROGRAM BACKGROUND

The LRMBS Program is a four-year program to improve water management in the Litani River Basin in the Bekaa. It is undertaken by IRG, in cooperation with LRA, and is funded by USAID. The program began in October 2009 and has four components: 1) Building institutional capacity; 2) Water monitoring, 3) Irrigation management; and4) Risk management.

QARAOUN DAM AND SEDIMENTATION

Qaraoun Dam was built in the early 1960s at the southern end of the Bekaa valley, between the villages of Qaraoun and Aitanit. From a riverbed altitude of 800m, it is a 60m-high rockfill dam with 220 million cubic meters of storage capacity, and a free spillway at elevation 858 meters (ASL).

Qaraoun Dam is operated by the Litani River Authority, and the stored waters are mostly used to generate electricity through a cascade of three hydropower plants (Markabe, Awali, and Joun). A small portion of the waters is used for irrigation, either through pumping (into the Canal 900 system on the left bank) or through release into the Lower Litani River (for irrigation of the coastal Kasmiye area).

The river basin supplying the lake is the central and south Bekaa, sandwiched between the eastern slopes of Mount Lebanon and the western slopes of Anti-Lebanon, both composed mainly of fractured karstic limestone of the Cretaceous (Cenomanian and Jurassic). These are characterized by **high permeability** and are subject to **erosion** and **weathering** (chemical and mechanical).

The area receives substantial precipitations (as compared to the rest of the Middle-East), but only during the winter season. Between December and April, winter clouds coming from the Mediterranean Sea break over Mount Lebanon (and the Anti-Lebanon) and generate thunderstorms and even snowfalls. As a result, streams and rivers on the two slopes have irregular flows, with extreme discharges if not floods during major storms and at snowmelt. Erosion and sediment transportation also occur.

But once flows reach the Bekaa valley, they slow and spread out, as the valley is almost flat with little slope (0.1 to 0.5%). As a consequence, most solid transportation settles at the foot of both slopes, and does not reach the river. It is thus expected (but to be checked) that sedimentation would not be a

serious concern for Lake Qaraoun, as it can be for other dams built in mountainous and dry countries (for example in Morocco and Tunisia).

The objective of the survey was to assess this sedimentation by carrying out a bathymetry of the reservoir, and comparing it to the valley geography before the construction of the dam, as provided through a 1950 topography map.

METHODOLOGY

The bathymetry survey was carried out by using a boat and a Doppler flow meter, the River Surveyor, both provided by LRBMS to the Litani River Authority. The River Surveyor is an Acoustic Doppler Profiler designed for accurate water flow and riverbed measurement and profiling. The M9 model used here has three types of sound beam producers, and can perform depth profiling with a range of 80 meters.
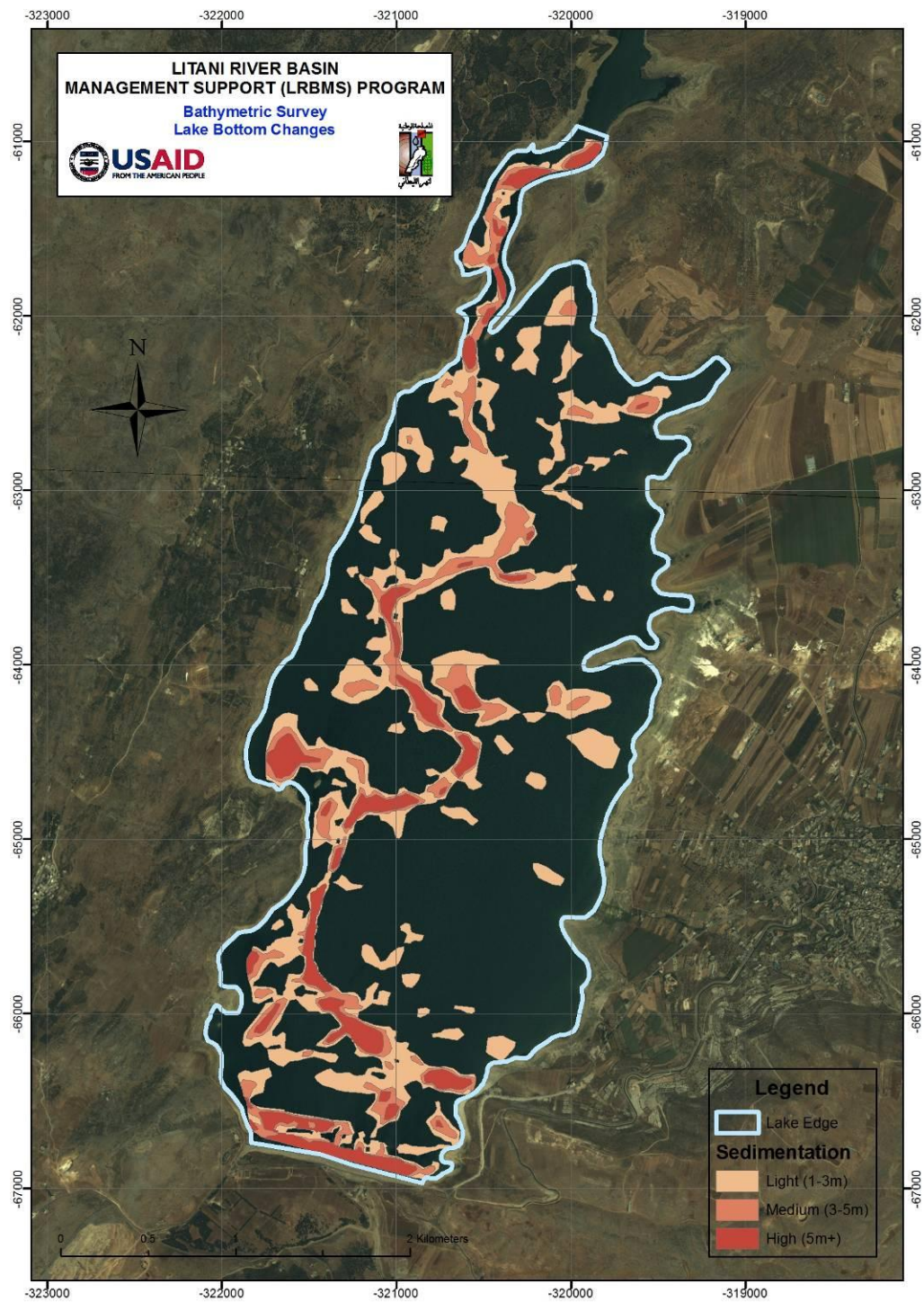
The boat made a series of about fifty East-West and West-East crossings/transects of the lake. The topography of the bottom was recorded during each transect. A complete new topography of the reservoir bottom was thus generated, using GIS software, and then compared to an old profile extrapolated from the 1950s topographic map.

RESULTS

GIS was first used to recalculate the original storage of the reservoir, about 207.5 Million cubic meters, as compared to the 1950s estimate of 222.8 Million cubic meters (a 7% slight over-estimate).

The newly calculated storage capacity of Qaraoun reservoir (2013), based on our bathymetry, is found to be **200.7 Million cubic meters, a loss of 6.8 Million cubic meters** due to sedimentation occurring naturally in the reservoir. This loss of only 3% in almost 50 years (since reservoir construction) shows that sedimentation is much reduced and the reservoir should provide storage for hundreds of years.

On the other hand, the dead storage, which is the volume of water trapped under the intake, has decreased from 2.9 Million cubic meters to 1.5 Million in the past 50 years. This is slightly less than the half revealing the possibility that the **sediments could reach the intake in another 50-60 years,** assuming sedimentation continues at the same rate. This is something that could jeopardize the operation of the dam and needs to be continuously monitored.

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Bathymetric Survey
Lake Bottom Changes

USAID
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Legend
Lake Edge
Sedimentation
Light (1-3m)
Medium (3-5m)
High (5m+)

0   0.5   1   2 Kilometers

الملخص التنفيذي

لمحة عن المشروع

مشروع الــ LRBMS هو برنامج لأربع سنوات يهدف لتحسين الإدارة في حوض نهر الليطاني في محافظة البقاع. يتم تنفيذه من قبل المجموعة الدولية للموارد IRG، بالتعاون مع المصلحة الوطنية لنهر الليطاني وبتمويل من الوكالة الأمريكية للتنمية الدولية. بدأ البرنامج أعماله في تشرين الأول / أكتوبر 2009 ويتألف من أربع مكونات 1) بناء القدرات المؤسسية 2) مراقبة المياه 3) إدارة الري و 4) إدارة المخاطر.

سد القرعون والترسبات

تم إنشاء سد القرعون في مطلع الستينات من القرن الفائت عند الطرف الجنوبي لسهل البقاع، بين قريتي القرعون وعيتنيت. فوق مجرى نهر على ارتفاع 800 متر فوق سطح البحر، يرتفع السد الركامي 60 مترًا وتبلغ قدرته الاستيعابية 220 مليون مترًا مكعّبًا، بالإضافة لقناة تفريغ بالجاذبية على ارتفاع 858 مترًا فوق سطح البحر.

سد القرعون تديره المصلحة الوطنية لنهر الليطاني، وتُستخدم المياه المخزنة خلفه بمعظمها لتوليد الطاقة الكهربية من خلال سلسلة من ثلاث محطات كهرمائية (مركبا، الأولي وجون). جزء بسيط نسبيًا من هذه المياه يتم استخدامها للري، إمّا من خلال الضخّ (الى قناة 900 على الضفة اليسرى) وإما من خلال تسريحها إلى الحوض الأسفل لنهر الليطاني (حيث تستخدم في مشاريع ري القاسمية على الساحل).

يتغذى المجمع المائي (البحيرة) في القرعون من حوضي البقاعين الأوسط والجنوبي، اللذان تحتويهما سلسلتي جبال لبنان الشرقية والغربية، واللتان تتألفان بشكل أساسي من الصخور الكلسية الكارستية العائدة للعصر الكريتاسي (الأوسط السينوماني والأعلى الجوراسي). هذه الصخور تتميز بمساميتها العالية (تخزين المياه) وهي عرضة لعوامل التجوية والتعرية (الحت الميكانيكي والكيميائي).

تتلقى المنطقة كميات كبيرة من المتساقطات (بالمقارنة مع منطقة الشرق الأوسط)، لكن فقط خلال موسم الشتاء. بين شهري كانون الأول ونيسان، تتكسر الغيوم الماطرة القادمة من المتوسط فوق جبال لبنان مسببة بعض العواصف الرعدية أو حتى

الثلجية. بالتالي، تكون الأنهار والسيول على كلا السفحين ذات تدفق متغيّر، حيث تتدفق كميات قصوى لا بل تفيض الأنهار خلال العواصف وبعد ذوبان الثلوج. يصاحب ذلك ظواهر التعرية وانتقال المترسبات.

حين تصل المجاري النهرية إلى سهل البقاع، تتباطأ سرعتها وتتوسّع (أو تتشعّب) ، حيث أن السهل مسطح نسبيّا ويبلغ معدل انحداره ما بين 0.1 و0.5%. بالنتيجة، معظم المواد الصلبة المحمولة تترسب على قعر السفوح الجبلية على كلا الجابين (الشرقي والغربي) ولا تصل الى النهر. بناء على ذلك يُعتقد (ولكن يجب التحقق) أن الترسبات لن تتسبب بمشكلة حقيقية لبحيرة القرعون، كما هي الحال في بعض السدود المبنية في مناطق جبلية في البلدان الجافة (مثلاً تونس والمغرب).

الهدف من هذه الدراسة هو تقييم هذه الترسبات بتوسّل سبر أعماق المجمع المائي، ومقارنتها بجغرافية الوادي قبل إنشاء السد، كما تظهرها الخريطة الطوبوغرافية للعام 1950.
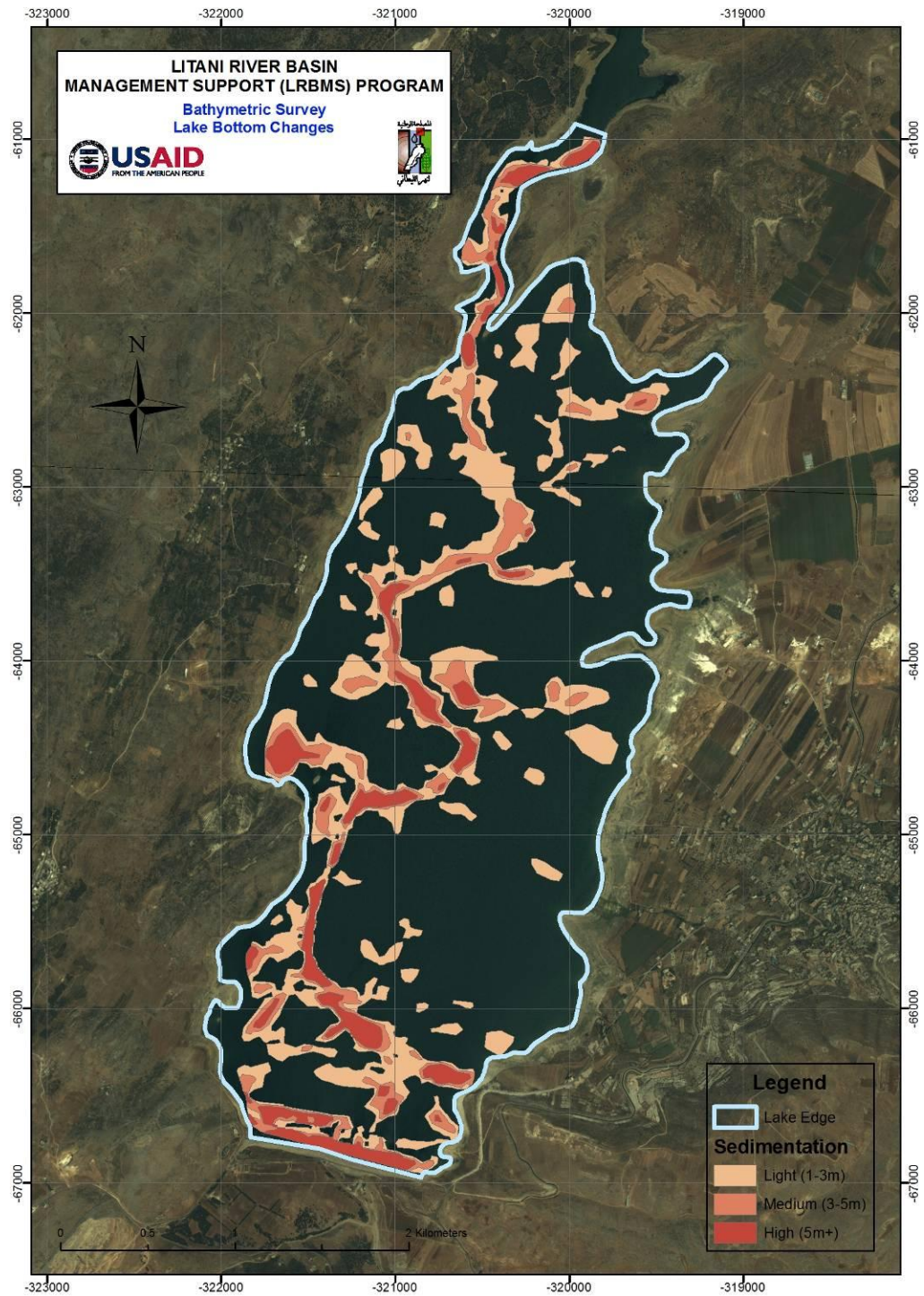
أسلوب البحث المعتمد

عملية سبر الأعماق تمت باستخدام زورق مطاطي ومقياس جريان دوبلر ®RiverSurveyor، وهما تقدمة من برنامج LRBMS للمصلحة الوطنية لنهر الليطاني. الجهاز عبارة عن مسبار صوتي يعمل بتأثير دوبلر مصمم خصّيصًا للقياسات الدقيقة لجريان الأنهر ومسح قاع الأنهر وسبر الأعماق. الموديل M9 المستخدم في هذه الدراسة يحتوي ثلاثة فئات من باعثات الحزم الصوتية، ويمكنه سبر أعماق قد تصل إلى 80 مترًا.

تم القيام بسلسلة من حوالي خمسين مقطعًا عرضيًا شرق غرب وبالعكس في البحيرة. وتم تسجيل طوبوغرافية القعر في كل مرحلة من المراحل. وتم بالنهاية إنشاء مخطط طوبوغرافي جديد للقعر، بواسطة نظام المعلومات الجغرافية، ومن ثم مقارنة النتائج مع مخطط استُلخص من خريطة طوبوغرافية تعود للعام 1950.

النتائج

أولا استخدم نظام المعلومات الجغرافية من أجل إعادة احتساب الحجم الأساسي المتاح للتخزين والذي بلغ 207.5 ملايين مترًا مكعبًا مقارنة بالحجم المقدّر في العام 1950 والبالغ 222.8 مليونًا (بفارق 7% مع مبالغة بسيطة في التقدير).

القدرة الاستيعابية الحالية لخزان القرعون (2013)، وبالاعتماد على الدراسة بين أيديكم، بلغت 200.7 مليون متر مكعب، أي خسارة ما يقارب 6.8 مليون بسبب الترسبات الطبيعية في الخزان. بالتالي فإنّ هذه الخسارة التي تشكل 3% فقط من مجمل التخزين المتاح بعد مرور 50 عامًا على إنشاء السد، تظهر أن ظاهرة الترسب محدودة والخزان يمكنه تأمين المياه لمئات السنين.

ولكن في المقلب الأخر، المخزون الميت، وهو مجموع المياه المحتجزة تحت فتحة برج التصريف (815 مترفوق سطح البحر)، انخفض من 2.9 مليون إلى 1.5 مليون متر مكعب أثناء 50 عامًا. ما يعني أن نصف المخزون تقريبًا قد امتلأ بالترسبات، ما يشير إلى إمكانية وصول المترسبات إلى مستوى فتحة التصريف في الــ50 أو 60 سنة القادمة، على فرض أنّ الترسب سيستمر بنفس الوتيرة. الأمر الذي قد يعرض تشغيل السد للخطر لذا يجب مراقبته بشكل مستمر.

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Bathymetric Survey
Lake Bottom Changes

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N

Legend

Lake Edge

Sedimentation

Light (1-3m)

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0   0.5   2 Kilometers

1. INTRODUCTION

1.1. AUTHORIZATION

International Resources Group (IRG) was contracted by USAID/Lebanon (Contract EPP-I-00-04-00024-00 Task Order No. 7) under the Integrated Water and Coastal Resources Management Indefinite Quantity Contract (IQC) II to implement the Litani River Basin Management Support (LRBMS) Program. The period for performance of the contract is September 29, 2009 to September 30, 2013.

1.2. PROGRAM OBJECTIVES

The purpose of the LRBMS Program is to set the ground for improved, more efficient and sustainable basin management at the Litani river basin through provision of technical support to the Litani River Authority and implementation of limited small scale infrastructure activities.

The LRBMS program is part of USAID's increasing support for the water sector in Lebanon. The Litani River Basin suffers the fate of many river basins around the world: increasing demands compete for limited natural resources. Groundwater over-exploitation, deforestation and overgrazing, unplanned urban sprawl, untreated wastewater effluents, and unsustainable agricultural practices contribute to environmental degradation in the form of declining water and soil quality.

Solutions do exist to reverse these trends and establish sustainable management practices. The key to successfully implement such solutions requires applying the principles of Integrated Water Resources Management (IWRM) through a single river basin authority rather than multiple agencies responsible for different aspects of water management as is the case in many countries. Fortunately, the existence of the Litani River Authority (LRA) provides a unique platform to become such an IWRM river basin authority that will mobilize stakeholders in the river basin and address these challenges in an integrated manner. Successful implementation of LRBMS will prepare the LRA to assume the role of an integrated river basin authority upon the removal of the present legal constraints.

1.3. PROGRAM COMPONENETS

LRBMS works with national and regional institutions and stakeholders to set the ground for improved, more efficient and sustainable basin management at the Litani River basin. The LRBMS technical assistance team provides technical services and related resources to LRA in order to improve their

planning and operational performance and equip them with the necessary resources for improved river basin management.

To achieve the program objectives, LRBMS undertakes activities grouped under the following four components:

1) Building Capacity of LRA towards Integrated River Basin Management

2) Long Term Water Monitoring of the Litani River

3) Integrated Irrigation Management with two sub-components:

   a) Participatory Agriculture Extension Program: implemented under a Pilot Area: West

   b) Bekaa Irrigation Management Project

   c) Machghara Plain Irrigation Plan

4) Risk Management with two sub-components:

   a) Qaraoun Dam Monitoring System

   b) Litani River Flood Management Model

1.4. PURPOSE AND CONTENTS OF THE REPORT

This report presents the methodology and results of a bathymetric survey of Qaraoun Lake, main water reservoir in Lebanon. This reservoir, built in the early 1960s, has never been assessed for sedimentation, which is a serious concern for reservoirs worldwide as transported solids and sediments can, over the years, accumulate and reduce the storage volume.

The objective of this bathymetric survey is to define the current storage capacity of Qaraoun lake and to assess the change since construction, this change being mainly due to sedimentation. This report includes four chapters beyond the current introduction:

- Chapter 2 provides basic facts about Qaraoun Dam and reservoir, and considerations regarding the reservoir's potential sedimentation;

- Chapter 3 lists the available data;

- Chapter 4 explains the methodology used for the current survey; and

- Chapter 5 presents and comments on the results of the survey.

2. QARAOUN DAM AND RESERVOIR

2.1. THE DAM

2.1.1. MAIN FEATURES

Qaraoun Dam was built at the southern end of the Bekaa valley, between the villages of Qaraoun and Aitanit. From a riverbed altitude of 800m, it is a 60m-high rockfill dam with 220 million cubic meters of storage capacity, and a free spillway at elevation 858 meters (ASL).

Qaraoun Dam is operated by the Litani River Authority, and the stored waters are mostly used to generate electricity through a cascade of three hydropower plants (Markabe, Awali, and Joun). A small portion of the waters is used for irrigation, either through pumping (into the Canal 900 system on the left bank) or through release into the Lower Litani River (for irrigation of the coastal Kasmiye area).

2.1.2. HISTORY

This dam was built in the early 1960s, and is the largest dam in Lebanon.

Eng. Ibrahim Abd El-Al published a detailed study on Litani Hydrology in1948 where he proposed the construction of a dam at the Qaraoun region, with double purpose "irrigation and power production". The economic feasibility of the dam was studied by the US Bureau of Reclamation in the early 1950s. The Litani River Authority was established in 1954, and the works were started with a multiple arch design. Unfortunately the 1955 earthquake partially destroyed and stopped the ongoing works. After additional studies, a rockfill design was adopted and the construction resumed in 1958, and was completed in 1963. The reservoir was then filled progressively and reached full-level end of 1965. It has been operated satisfactorily since.

2.1.3. DAM SITE AND CONSTRUCTION

The dam was ideally built at the southern end of the Bekaa valley, where the Lebanon and Anti-Lebanon mountains close up and create a bottleneck. The wider and flat area north of the dam provides for a large storing space. The dam location is also a profile change for the Litani river, which from a slow valley plain (slope 0.1-0.5%), turns downstream into a mountain torrent cascading down in a gorge (slope 4-10%).
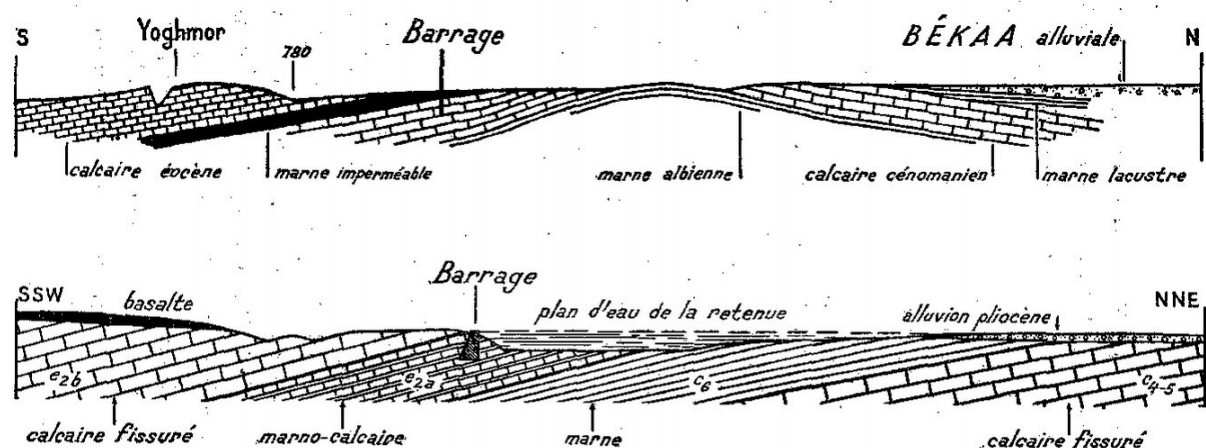
Figure 1 POSITION OF QARAOUN DAM, RELATIVE TO GEOLOGOCAL FORMATIONS. S-N: 1/200000, SSW-NNE: 1/25000

Most of the materials (mainly rocks) used for the construction of Qaraoun Dam were taken from a quarry in Mashghara, downstream and up on the right bank of the river. Even though, several local and limited excavation were done near the building site (upstream) where it has been found that the extracted material could be suitable for the building requirements and it was a more economical solution than importing gravels from further quarries.

2.2. THE RESERVOIR

2.2.1. DESCRIPTION

Lake Qaraoun, as all man-made reservoirs, changes seasonally depending on the amount of water received and used. At its maximum, it extends about 6km north-south and 2 km east-west, with a stored capcity estaimted at 220 Mm3.

2.2.2. GEOMORPHOLOGY

The Bekaa valley is a synclinal elevated at 900 meters above sea level by the great Jurassic elevation, sandwiched between Mount Lebanon to the West and the Anti-Lebanon mountain range to the East.

Qaraoun Lake sits on Quaternary formations comprised mainly of alluvial deposits of clay, silt, sand and gravel The eastern slopes of Mount Lebanon and the western slopes of Anti-Lebanon are composed mainly of fractured karstic limestone of the Cretaceous (Ceno.manian and Jurassic). These are characterized by **high permeability** and are subject to **erosion** and **weathering** (chemical and mechanical).
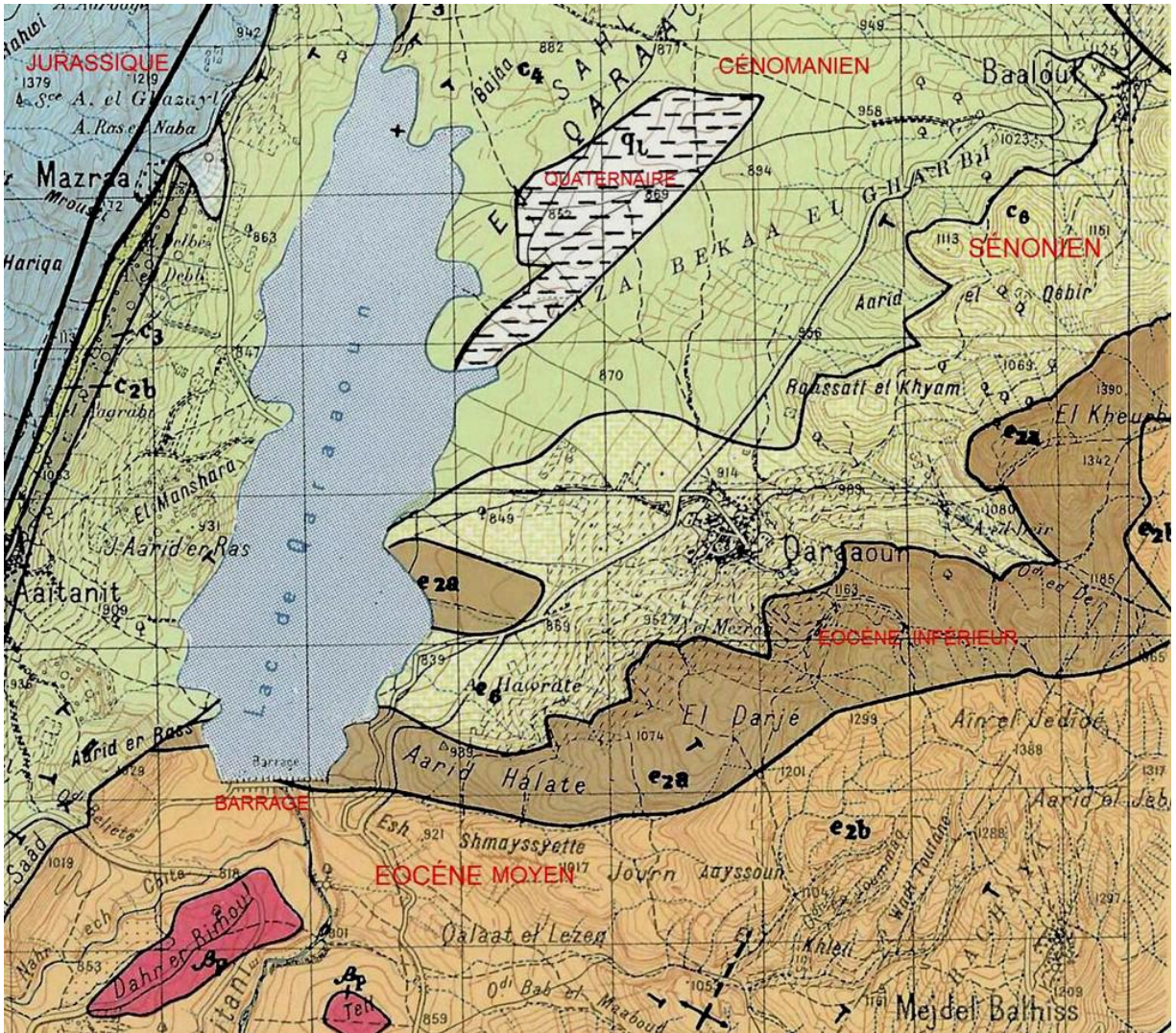
Figure 2 Geologic Map Of Qaraoun Dam Region (DUBERTRET 1953).

2.2.3. INFLOWS, FLOODS AND SEDIMENT TRANSPORTATION

Lake Qaraoun is supplied by the Litani River and its tributaries, the main ones being the Hala-Yahfoufa and the Ghzayyel on the left bank, the Berdawni and the Hafir-Jair on the right bank. This upper Litani River Basin covers the central and South Bekaa valley (about 1500 km2).

The area receives substantial precipitations (as compared to the rest of the Middle-East), but only during the winter season. Between December and April, winter clouds coming from the Mediterranean Sea break over Mount Lebanon (and the Anti-Lebanon) and generate thunderstorms and even snowfalls. As a result, streams and rivers on the two slopes have irregular flows, with extreme discharges if not floods during major storms and at snowmelt. Erosion and sediment transportation are also important.

But once flows reach the Bekaa valley, they slow and spread out, as the valley is almost flat with little slope (01 to 0.5%). As a consequence, most solid transportation settles at the foot of both slopes, and does not reach the river. It is thus expected (but to be checked) that sedimentation would not be a serious concern for Lake Qaraoun, as it can be for other dams built in mountainous and dry countries (for example in Morocco and Tunisia).

3. EXISTING DATA

The main source of information regarding the past topography of the reservoir (before construction of the dam), is a 1950 topographical maps that shows 5m contour lines.
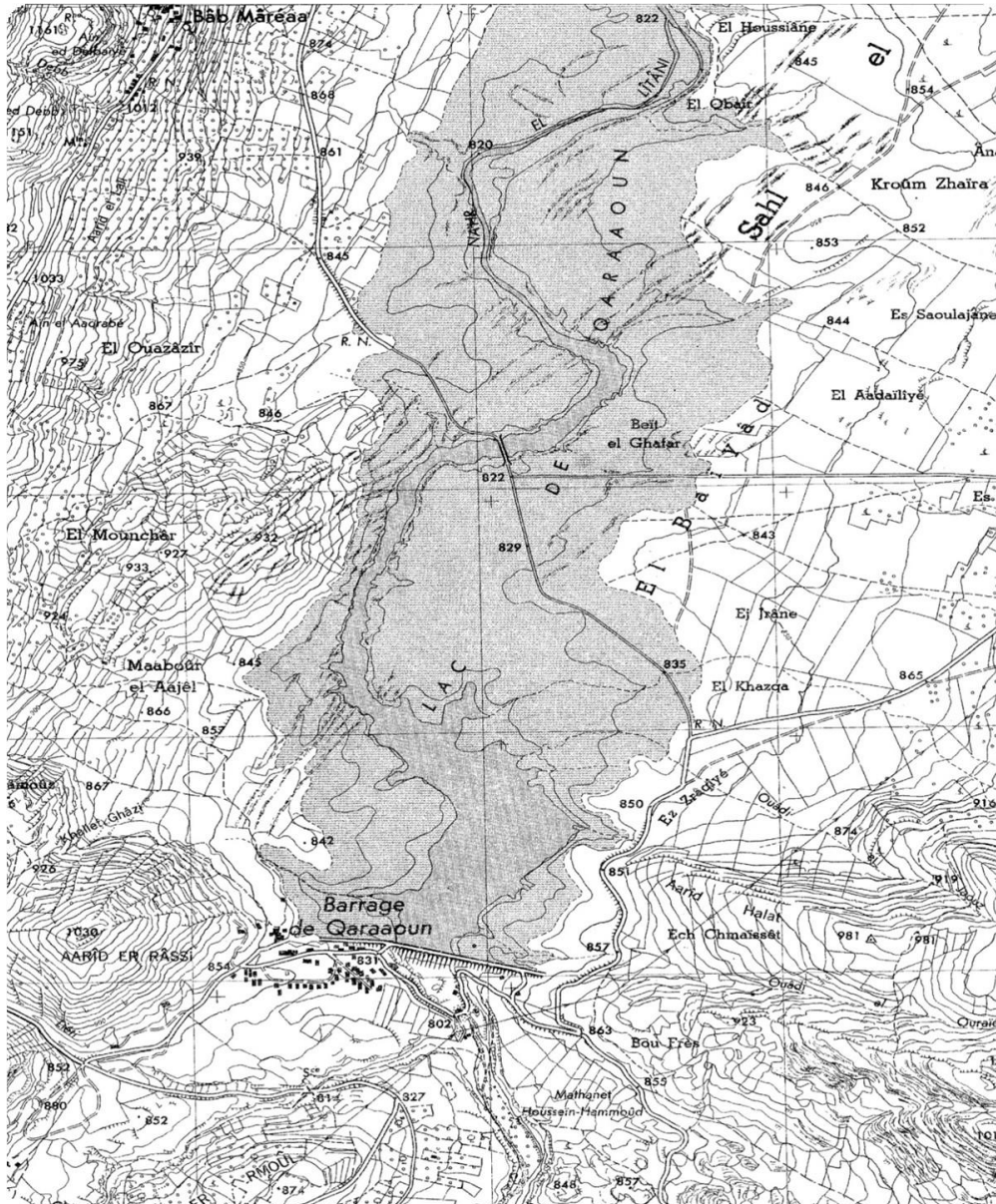

Figure 3: Topographic map of Qaraoun Reservoir area 1950

Based on this map, the storage capacity was estimated for the feasibility study of Qaraoun Dam, and both elevation/volume graph and table were prepared and have been used since by the LRA to assess the stored volumes based on the reservoir elevation.

This data is reasonably sound but does not have the density and accuracy that modern tools can provide (between two 5m contour lines, the ground in-between can slope different ways, from a progressive slope to an abrupt fall or cliff).

4. SURVEY EQUIPMENT AND METHODOLOGY

4.1. METHODOLOGY

The bathymetry survey was carried out during the period between May and August 2013 by using a boat and a Doppler flow meter, the River Surveyor, both provided by LRBMS to the Litani River Authority.

The boat made a series of about fifty East-West and West-East crossings/transects of the lake. The topography of the bottom was recorded during each transect. A complete new topography of the reservoir bottom was thus generated, using GIS software, and then compared to the old profile extrapolated from the 1950s topographic map.
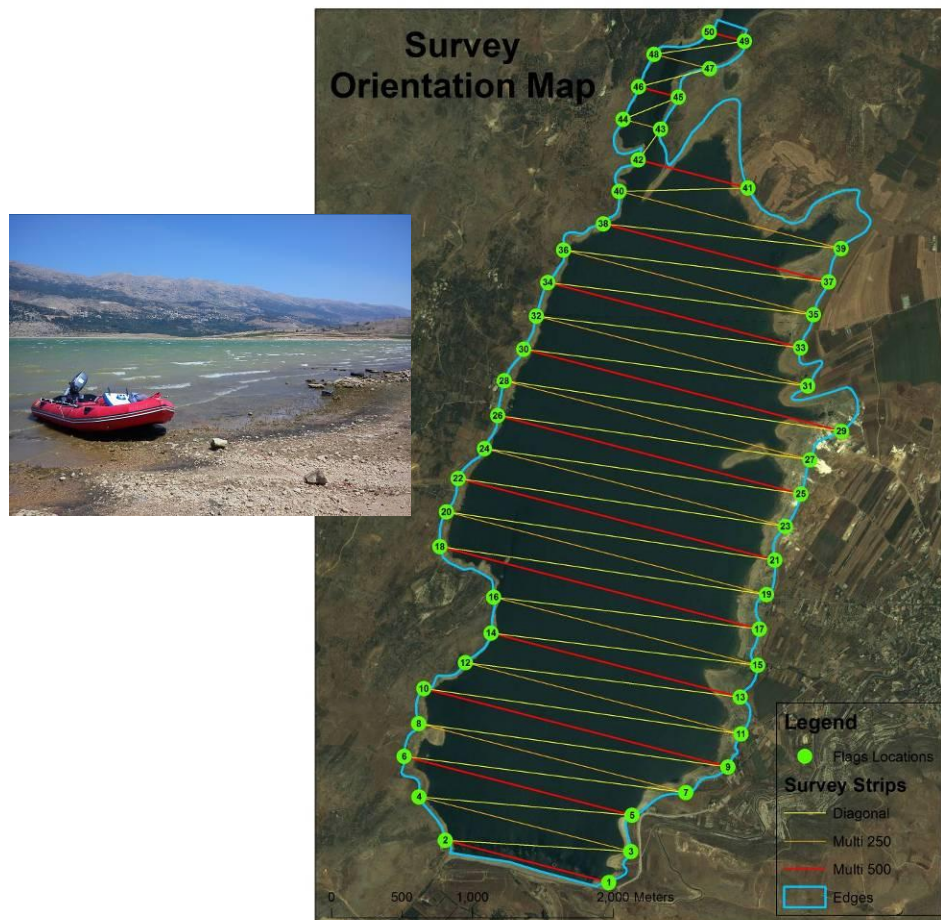

Figure 4: The planned surveying transects.

4.2. EQUIPMENT (RIVERSURVEYOR®)

River Surveyor (RS) is a floating Acoustic Doppler Profiler designed for accurate water flow and riverbed measurement and profiling. The M9 model that we used in our survey, has two types of sound beam producers, one vertical (0.5 MHz) and dual four near-vertical (horizontal, up to 3.0 MHz), the first is designated for depth profiling with a maximum range of 80 meters (knowing that the maximum depth in Qaraoun Reservoir is about 60 meters). The latters are more efficient with flow measurements since they use the Doppler Effect while the boat (or hydroboard) is moving to calculate the water velocity all along the underlying water column, then the flow can be internally calculated.

The resolution of the vertical beam is under the 0.001 m, giving the device a superior accuracy rate, an making it suitable for the goal of our assignment.

The Riversurveyor® M9 is composed of several electronic devices which can be mounted on a floating resistant board (Hydroboard®). It includes:

a. Acoustic Doppler Profiler ADP: the main devise containing an internal computing system, which makes all the necessary calculations and data conversions.

b. Power and communication module: contains the rechargeable batteries and the communication ports to connect all the other devices together.

c. The GPS antenna: it can be attached by thumb screws on either the ADP or PCM

4.3. MEASUREMENTS

4.3.1. THE SPILLWAY SCALE AS ALTIMETER

During all phases of our survey, the GPS was used for positioning and track reference. Knowing that GPS has a wide accuracy for elevation measurements, we looked for a better alternative. The water level scale attached to the spill way was a steady, thus reliable, reference. The accuracy of the scale was verified by total stations.

Figure 5 Water Level Scale attached to the spillway

4.3.2. RIVERSURVEYOR OPERATION

To operate the Riversurveyor, "the man on board" has the option to use a Bluetooth enabled computer, or a handheld mobile device, where the appropriate software must be installed. The RiverSurveyor Live or RSL is a user-friendly interface, giving the monitor the ability to operate the RS, calibrate the compass and off course observe the whole profiling process in real time.

4.3.2.1. CONNECTION

First, the computer (or the mobile device) must be connected to the RS through the appropriate connection port, this can be made directly using the provided direct connection cable, or through Parani Bluetooth dongle, which have a maximum range of 200 m. However, the mobile device Bluetooth has a maximum range of 60 m only.

4.3.2.2. PRE-MEASUREMENT STEPS

The compass calibration, which must be done before every measurement, is a very important procedure and was done very carefully, using the calibration utility shown on the "smart page" of RSL software. The GPS compass (already mounted on the hydroboard), must be turned in a complete circle twice in – not less than – two minutes, while moving it back and forth and in 8 pattern, to assure that the compass reached an inclination angle higher than the maximum expected pitch and roll during the measurement.

A good attention to details must be paid during the input of system setting, especially the actual transducer depth, the magnetic declination and the water salinity. The track reference must be set to GPS-GGA, and the depth reference to "Vertical Beam".

4.3.2.3. TRANSECT MEASUREMENT

Once in water, the hydroboard was attached to a motor operated zodiac using a stick and elastic rope to reduce oscillation, the predefined pathways were maintained by using a handheld GPS receiver. The survey was done in several discontinued transects, in order to minimize the error to the minimal possible rate, and to make sure that no much data is lost in case of an unforeseen problem (battery failure, heavy winds, curious fisherman …). A minimum boat speed was maintained all the time; this helps in enhancing the accuracy and preserving conformity all along the process.
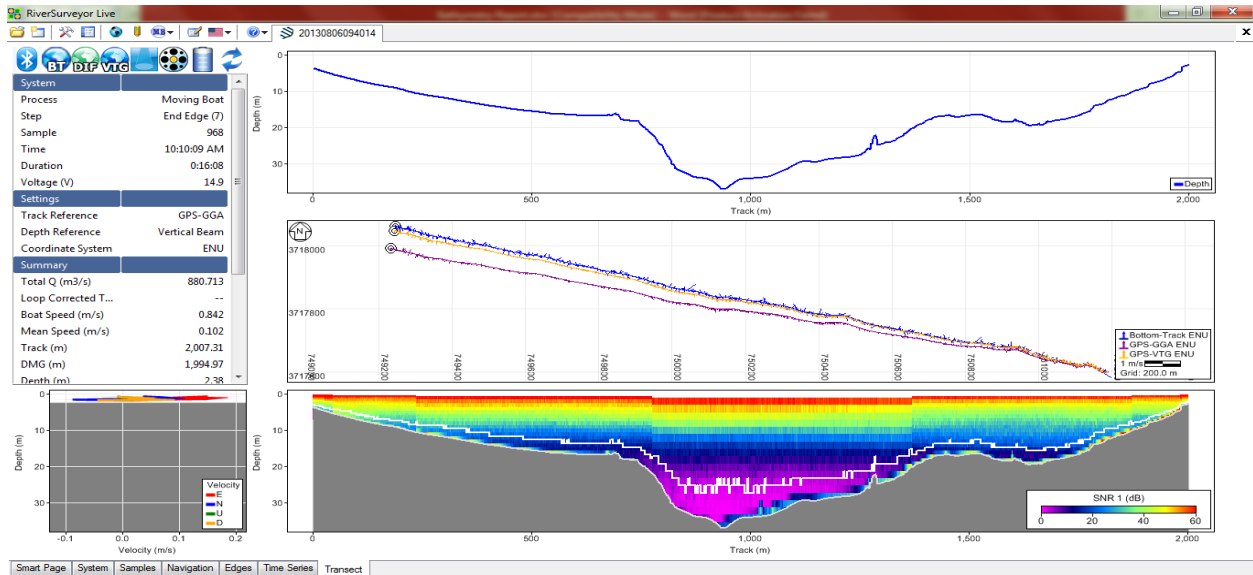

Figure 6 Snapshot of RSL during Qaraoun bathymetry survey

4.3.3. GROUND CONTROL POINTS

Before comparing the new bathymetry to the old topography, both datasets must be adjusted to the same reference. To do so, a surveyor was hired to take several ground control points (GCPs) around the lake in order to compare the heights with the old topography. These GCPs are based on the official Lebanese Geodetic Network, which was created and maintained by the Geographic Affairs Department in the Lebanese Army.

The 10 GCPs that were taken at the edge of the river showed 0.08m of relative difference (after removing two inaccurate points), which shows rather good correspondence between the two topographies.

Similarly, in order to guarantee that the water level measured at the spillway belongs to the same reference system as the other dataset, the surveyor compared it to a near GCP through a leveler and the difference was found minima.

The following picture shows the locations of the reference points used and the local difference between the newly found altitude and the one retrieved from the 1950's map.

Figure 7 Ground control points

4.3.4. BATHYMETRIC SURVEY PLAN

The RiverSurveyor uses two different types of sound beams, vertical and near vertical (horizontal), only the vertical one is to be used for depth profiling since it is more appropriate and accurate. This lead to a coverage problem where we needed to cover the maximum possible surface. To do so a sharp angled zigzag pattern was used as seen in the following picture. The lines were kept as straight as possible using a handheld GPS device to guide the motor boat.
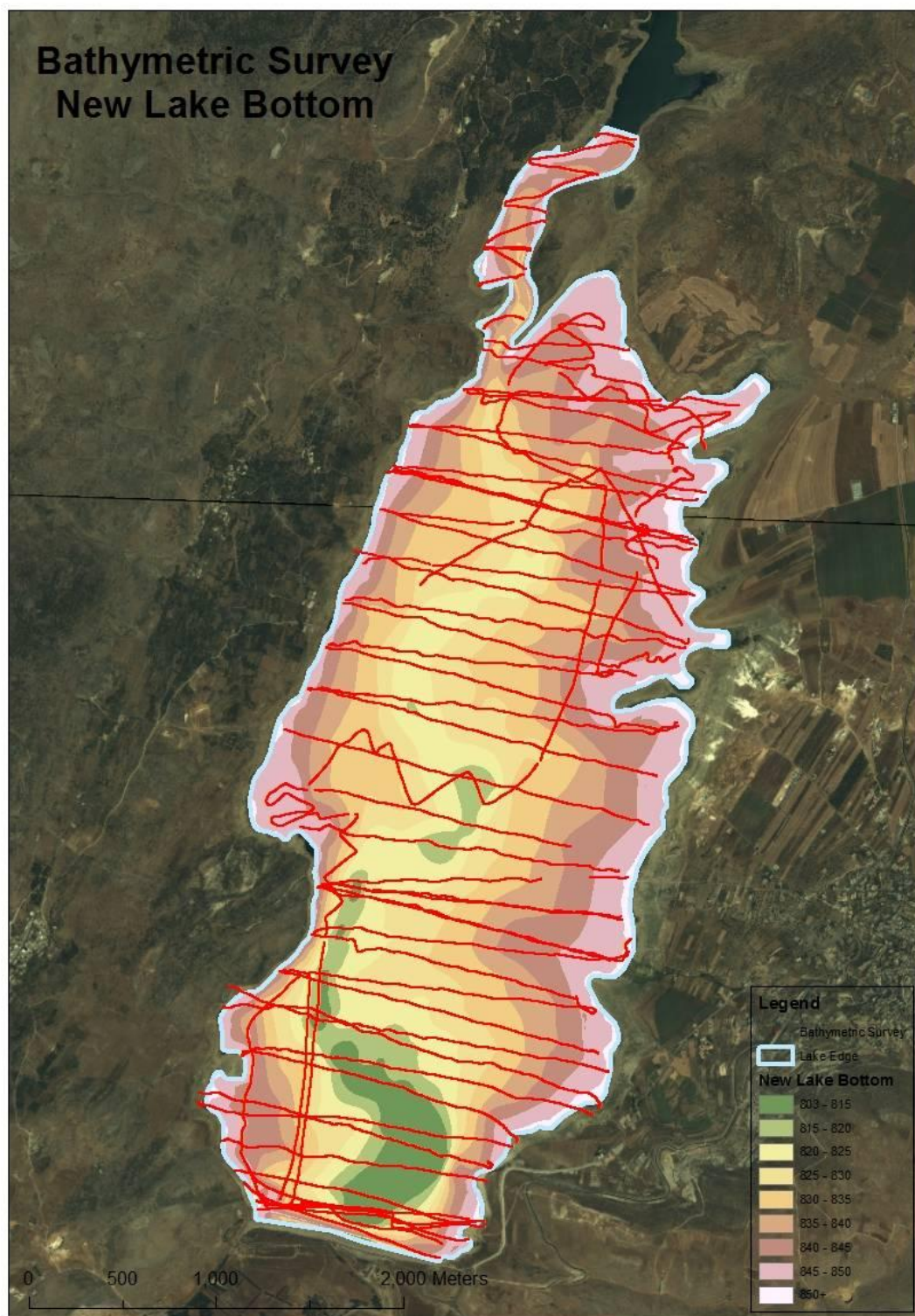
Figure 8 the Qaraoun reservoir bathymetric map, showing the covered pathways.

4.3.5. GIS PROCESSING OF BATHYMETRIC DATA

Once all the bathymetric survey was done, and all the surveying data was extracted into excel sheets, the GIS processing was divided into 3 phases:

4.3.5.1. DATA PREPARATION

The 1st phase was to prepare the data to become GIS-ready for the analysis. This phase included the following steps:
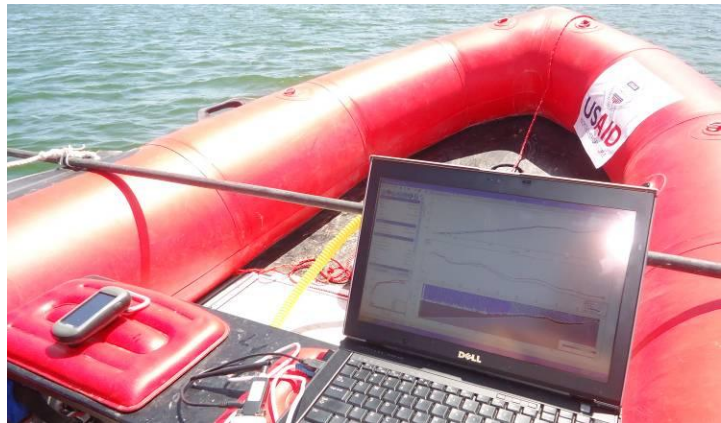
i. Calculate the altitude of the bottom for each sample as follows: Z = Water Level - Depth;
ii. Convert the excel sheet into a GIS layer based on the locations of the samples;
iii. Project the data from Geographic coordinate system (WGS 1984) into the local official coordinate system (Stereographic projection) in order to match the other dataset.

4.3.5.2. DATA INTERPOLATION

Once all the samples are GIS-ready and coincident to the old topography, the next phase was to generate a continuous surface based on the samples bottom altitude. The generation of this surface is achieved through the technique of interpolation which estimates the values at locations away from the samples based on the density of the samples and their distribution.

Interpolation can be achieved differently depending on the algorithm used. There exist several algorithms, called interpolators, and each one of them is best suitable depending on the nature of the interpolated data and the density and distribution of the samples. In the case of this task, the most suitable interpolator found was the 'Nearest Neighbor'.

4.3.5.3. DATA COMPARISON

Once the new bathymetry bottom was created, it can be compared to the old topography one. The difference was calculated as follows: Difference = New Bathymetry - Old Topography.

The results where then divided into 3 categories depending on the values:

- **-1.5 < Difference < +1.5**: No noticeable change between the two surfaces. This threshold was chosen as the accuracy of the old topography is approx. 1.6m and any change beneath this value is uncertain because it is within the margin of error;
- **Difference < -1.5**: the old topography is higher than the new bathymetry, and thus some lowering or slope failures are assumed to have taken place there;
- **Difference > +1.5**: the new bathymetry is higher than the old topography and thus some sedimentation or dumps are assumed to have taken place there.

4.4. DATA QUALITY CONTROL

The River Surveyor Live, which is the computer interface associated with the profiler, has the option to arrange all the collected measurements in the form of datasheets containing all the measured parameters and their derivatives (internal automatic conversions and calculations) all in one bunch of data. In addition to the required positioning information and depth readings, the system can provide actual measurement of the following:

- Voltage
- Pitch and roll (must be under the calibrated limit)
- GPS compass heading
- GPS quality / number of satellites in use
- HDOP (dilution of precision)

These meters were used during the measurement and when reviewing and post-processing the data to control and maintain the quality, accuracy and pertinence of the bathymetric survey.

4.5. ERROR ANALYSIS

Like any field study, this survey may have encountered some errors, either systematic, personal or random error. In the current study, the possible errors are identified as follows:

- Systematic error in the old topography map, resulting from the coarseness of data where the density of contour lines was relatively low (5 meters elevation).

- Systematic error of the total stations used during the Ground Control Points identification. The used apparatus has a general elevation precision of 3 cm for every 1 Km. knowing that the distance between successive points was between 200 and 300 meters, and the offset was in the acceptable limit when closing the loop.

- Systematic error of the RiverSurveyor®:

  a. Horizontal error: coming for the RTK-GPS device

  b. Vertical error: despite the high accuracy of the vertical beam (0.001 m), an error in depth measurement may still committed if the pitch and roll (horizontal rotation of the ADP due to water waves) was higher than the calibrated level. This was monitored by the before mentioned data quality meters during measurements in real time (see 5.1).

- Personal error: an error may slip out by the operator because of faulty procedure or misreading of a scale

- Random errors: which are the errors produced by unforeseen change in experimental conditions such as change temperature, salinity, magnetic declination, or any other external interference. This type of errors is unpreventable and is generally out of one's control.

5. RESULTS

5.1. MAPPING

The two dimensions transects recorded by the RiverSurveyor were gathered and plotted into one new bathymetric map using GIS tool. The following picture shows the new contour lines or isobaths of the Qaraoun reservoir.

As expected, the survey results disclosed the presence of variations in the reservoir bathymetric profile in comparison to the 1950's topographic map. The ground level (now the bottom of the lake) was subject to raises in some places (sedimentation) and losses in others (Lowering). The sedimentation/lowering obviously was not distributed evenly all around the reservoir, this differentiation occurred according to the following situations:

A- **Distance**: knowing that the water capacity to carry sediments decreases at lower velocity; the larger sized sediments are more likely to settle down near the mouth of the lake (upstream), while the small particles will relatively continue to float downstream and require more time to deposit.

B- **Depth and Slope**: The riverbed, which become a deep groove at the bottom of the reservoir, was rapidly filled up by sediments. The sediments, under the effect of gravity, deposit towards the deepest parts of the reservoir. On the other hand, the steeper slopes have higher risk of failure when submerged underwater.

C- **Geology**: when submerged by water, silt and sand become less stable, increasing the vulnerability of the subaqueous slope to failures. These failures may result from seismic activity, flush floods, or major construction works.

D- **Human activities** : according to the testimonies of elderly people met in Qaraoun village, the contractors, while building the Dam, have excavated some of the construction materials from nearby hilly land; they identified the digging location about 200 to 300 meters upstream of the actual Dam.
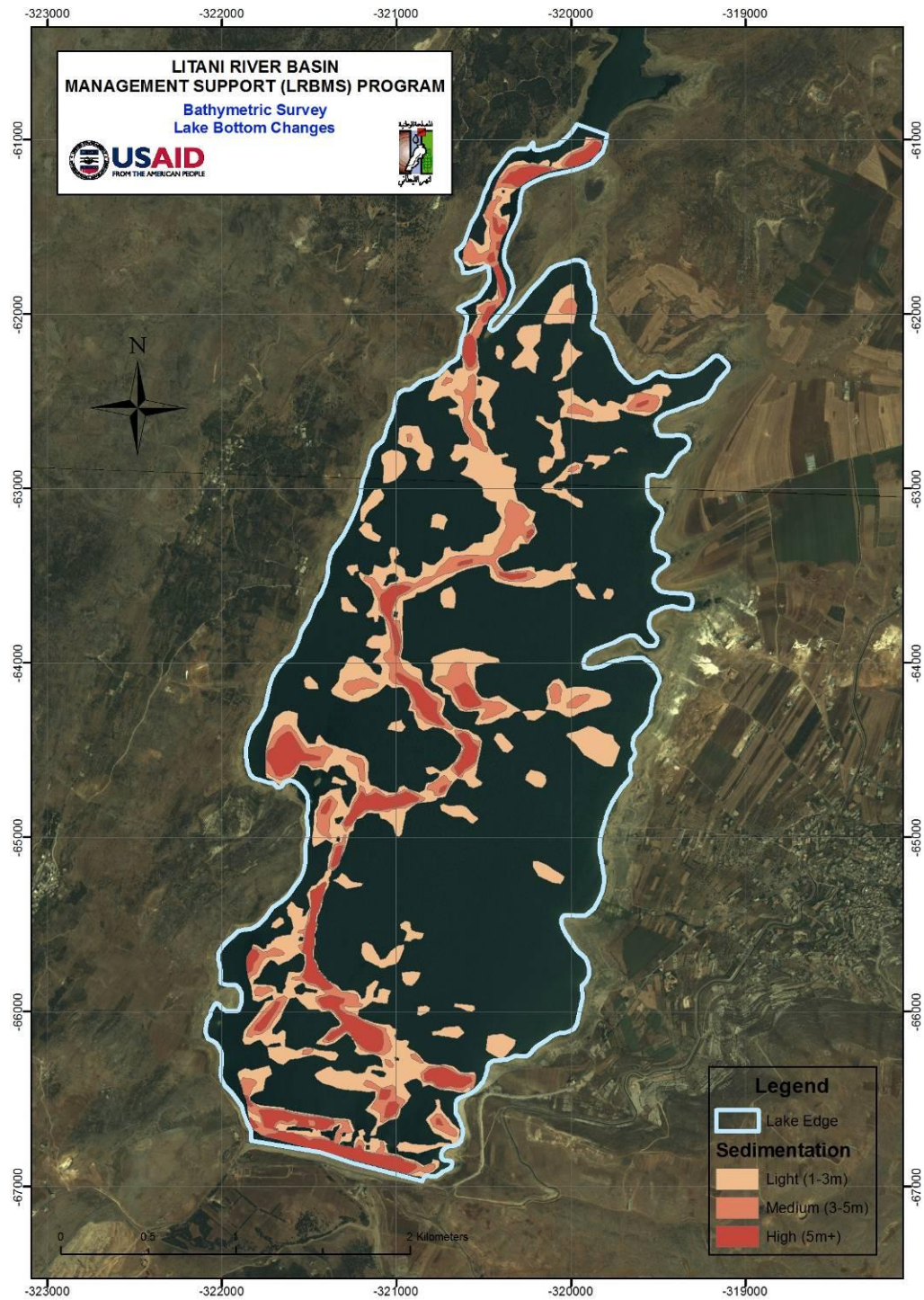
Figure 9 Map showing the difference between the new bathymetry and the old topographic map.

5.2. NUMBERS UPDATED

GIS was first used to recalculate the original storage of the reservoir which was found to be about 207.5 Million cubic meters, as compared to the 1950s estimate of 222.8 Million cubic meters (a 7% slight over-estimate).

The newly calculated storage capacity of Qaraoun reservoir (2013), based on our bathymetry, is found to be **200.7 Million cubic meters, a loss of 6.8 Million cubic meters** due to sedimentation occurring naturally in the reservoir. This loss of only 3% in almost 50 years (since reservoir construction) shows that sedimentation is much reduced and the reservoir should provide storage for hundreds of years.
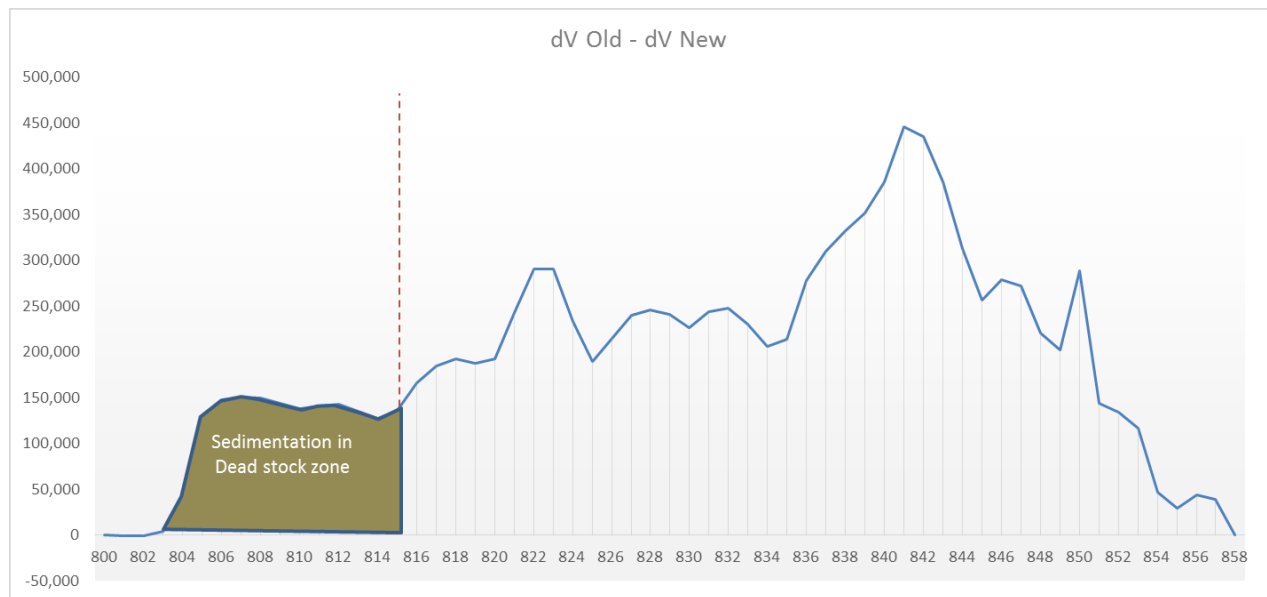

Figure 10 Graph showing the storage capacity loss (volume in cubic meters) in each one meter of elevation.

On the other hand, the dead storage, which is the volume of water trapped under the intake, has decreased from 2.9 Million cubic meters to 1.5 Million in the past 50 years. This is slightly less than the half revealing the possibility that the **sediments could reach the intake in another 50-60 years,** assuming sedimentation continues at the same rate. This is something that could jeopardize the operation of the dam and needs to be continuously monitored.
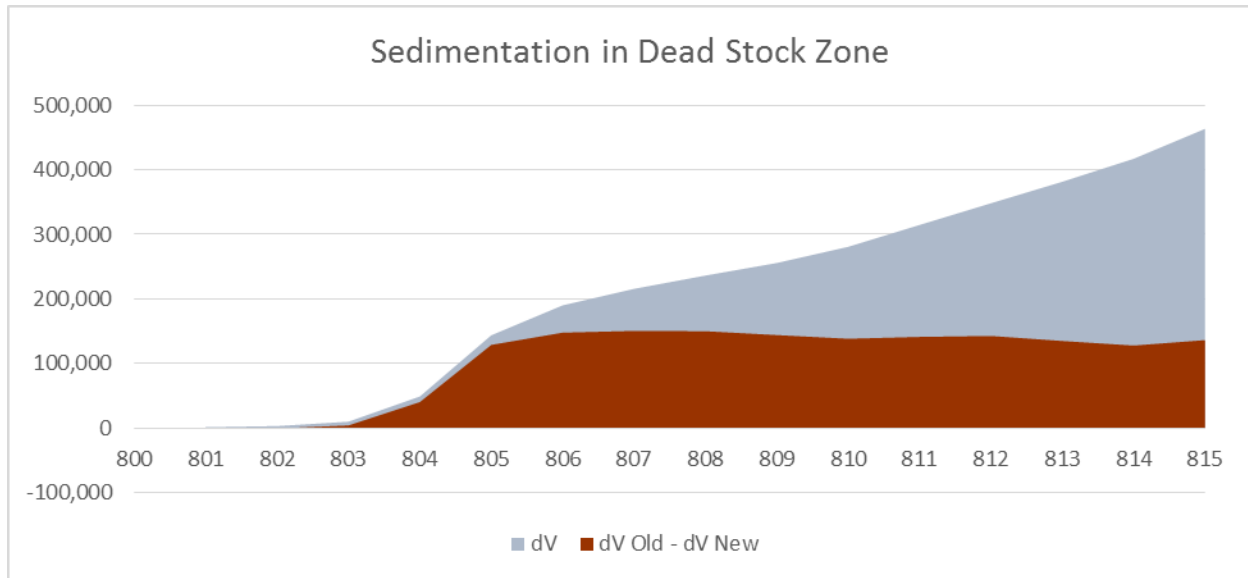
Figure 11 Graph showing the sedimentation volume compared to the original storage capacity in the Dead Stock Zone
(below 815 mASL)

5.3. THE NEW VOLUME/LEVEL CURVE

After establishing the new bathymetric profile, we were able to update the level/volume curve used by LRA staff as to determine the daily storage in the reservoir (see Annex I). The new volumes were extracted from GIS after taking into account the dead storage below the intake tower (815 mASL). Both the old topographic map and newly produced bathymetric map were analysed and compared. The following picture shows the difference between the different calculations.
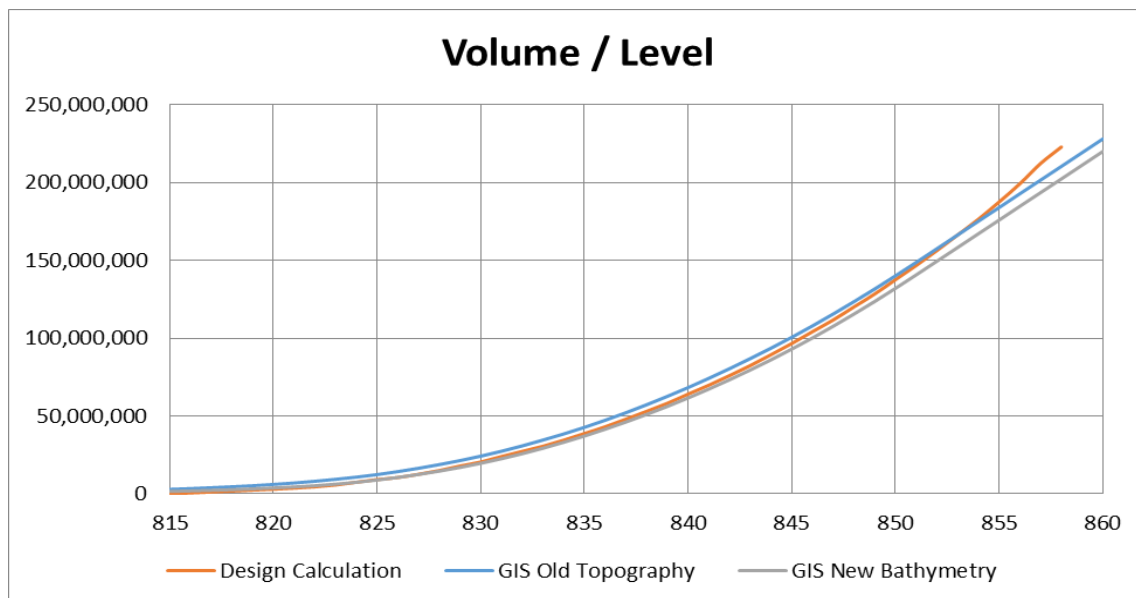
5.4. LEVEL/VOLUME TABLE

Table 1 Level/Volume table, comparison between LRA calculation, Old Topography Map, and the newly updated bathymetric profile (numbers are rounded to the nearest 100,000 cubic meters).

E	Existing LRA curve	GIS recalculation with 1950 Map	2013 Bathymetry	E	Existing LRA curve	GIS recalculation with 1950 Map	2013 Bathymetry
815	0	0.00	0.00	837	48,000,000	49,259,752.98	44,595,298.85
816	600,000	491,708.66	326,187.09	838	53,000,000	54,366,356.28	49,496,016.70
817	1,200,000	1,053,103.12	705,557.96	839	58,200,000	59,729,533.45	54,648,938.17
818	1,800,000	1,684,281.86	1,146,861.03	840	64,100,000	65,370,428.83	60,063,772.14
819	2,400,000	2,388,051.23	1,652,072.04	841	69,800,000	71,322,478.30	65,776,056.99
820	3,000,000	3,181,285.07	2,230,256.79	842	76,000,000	77,537,838.95	71,767,595.63
821	3,700,000	4,117,659.98	2,911,527.35	843	82,400,000	84,002,332.79	78,041,694.52
822	4,500,000	5,216,701.91	3,729,798.61	844	89,400,000	90,717,663.26	84,595,541.53
823	5,700,000	6,474,061.62	4,718,449.44	845	96,600,000	97,702,212.84	91,429,383.79
824	7,500,000	7,893,416.65	5,914,071.43	846	104,200,000	105,031,697.03	98,611,872.42
825	9,200,000	9,512,813.10	7,328,812.31	847	111,700,000	112,676,644.93	106,131,322.29
826	10,500,000	11,404,425.85	9,009,620.41	848	120,100,000	120,580,088.18	113,957,941.80
827	12,600,000	13,550,503.89	10,936,439.27	849	128,400,000	128,733,135.70	122,063,724.05
828	15,000,000	15,923,429.74	13,083,835.12	850	137,600,000	137,142,763.85	130,451,811.87
829	17,900,000	18,514,974.91	15,452,837.19	851	146,700,000	145,821,490.23	139,125,432.78
830	20,500,000	21,351,509.11	18,087,280.01	852	156,300,000	154,612,613.17	147,915,352.16
831	24,000,000	24,505,725.47	21,041,982.27	853	166,300,000	163,417,998.31	156,720,462.62
832	27,300,000	27,951,538.06	24,278,549.88	854	176,400,000	172,224,628.84	165,526,982.11
833	30,600,000	31,662,013.86	27,785,507.88	855	187,500,000	181,031,677.32	174,334,036.91
834	34,500,000	35,624,639.68	31,560,154.98	856	199,200,000	189,838,887.83	183,141,247.41
835	38,800,000	39,859,043.95	35,605,560.11	857	212,180,000	198,646,204.51	191,948,564.09
836	43,100,000	44,415,779.77	39,957,782.23	858	222,800,000	207,453,479.51	200,755,839.09

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